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HEATING OF DISPERSE POLYMER MATERIALS IN GAS-THERMAL SPRAYING

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The article presents the results of a comparison of the effectiveness of heating disperse polymers in gas-flame and in plasma streams.

A disperse polymer, fed into the jet of a gas-flame or plasma stream, is heated and sprayed onto the surface of the substrate in the molten state or in a state close to that [1, 2]. The degree of fusion of the material of the particles and the intensity of their interaction with the substrate depend on the intensity of the heat and mass transfer of the particles and of the stream. Experiments [1] showed that the number of particles per unit volume of the jet is also of importance.

Although approaches vary as regards the behavior of the particles in gas-thermal spraying because the entire complex of processes is very complicated, it is nevertheless generally accepted that the particle size and the properties of the material and the parameters of the hot stream have to be taken into account [1-3]. In most cases there is not heat exchange between the particle surface and the hot stream at the initial state of heating. It is usually assumed that the maximum temperature on the particle surface is established instantaneously, and that it remains unchanged during the entire period of the particle being in the stream [3]. Such an approach yields an approximate estimate of the size of the particles which are molten during the time they are situated in the hot medium. However, there are data [2] indicating that the heating of disperse materials is determined in particular by the intensity of the heat exchange of the particles with the gas stream impinging on them. In plasma spraying an important part is additionally played by the radiant heat flux coming from the heat source.

A typical diagram of the gas-thermal jet according to data of [1] is shown in Fig. 1; its analysis shows that the hot gas jet usually has the form of a truncated circular cone of length L with the bases F_1 and F_S ($F_1 \ll F_S$).

With a gas-flame jet the temperature on the axis of the stream at the burner attains 2800°K, then the temperature rapidly drops, and at a distance of 100 mm it amounts to about 800°K. In a plasma jet the temperature at the nozzle edge is estimated to be 20,000°K, and at a distance of 100 mm of the order of 1100-1200°K; the maximum temperature of an electric arc attains 32,000°K [1]. The rapid drop of the temperature of the stream with increasing distance from the nozzle edge is due to the supply of compressed gas and the intense ejection of atmospheric air into the jet. The air content in the plasma jet at a distance of 100 mm from the nozzle edge is up to 90%. The particles in gas-thermal spraying move at speeds of 50-150 m/sec in the plasma jet and with 20-50 m/sec in the gas-flame jet [2].

Neglecting the radial and longitudinal nonuniformity of the gas-thermal stream, the space—time pulsations of the heating zone, the ablation of the material of the particles, and the physicochemical processes of thermal and thermooxidation destruction of the polymers in order to simplify the theoretical model, we will examine the uniform heating of a spherical particle with radius r_p moving in a medium with approximately constant temperature T_m at speed v_p during time τ_{th} at approximately constant heat flux density $q = q_c + q_r$, where q_c is the

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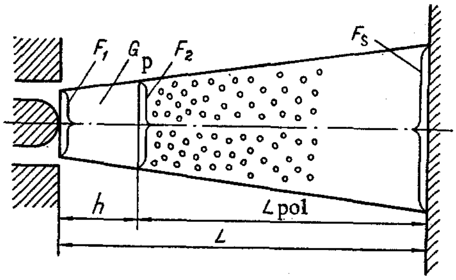

Fig. 1. Diagram of the jet for gas-thermal spraying.

heat flux to the particle due to convection, and q_r is the radiant heat flux acting on the surface of the particles and coming from the source of the high temperature, due to the dissipation of radiation on particles fed to the stream in the amount G_p with the temperature T_0.

In gas-flame spraying (the maximum temperature of the jet is relatively low, and consequently the proportion of the radiant component is insignificant) we examine as the first approximation of the problem of heating a spherical particle supplied with heat according to Newton's law in a medium with constant temperature, i.e., we solve an equation of heat conduction of the form [4]

$$\frac{\partial [rT(r, \tau)]}{\partial \tau} = a_p \frac{\partial^2 [rT(r, \tau)]}{\partial r^2} \quad (\tau > 0; \quad 0 < r < r_p) \tag{1}$$

with the initial and boundary conditions $T(r, 0) = T_0 = \text{const}; \ \frac{\partial T(0, \tau)}{\partial r} = 0; \quad T(0, \tau) \neq \infty;$

$$-\frac{\partial T(r_p, \tau)}{\partial r} + \frac{\alpha}{\lambda_p}[T_m - T(r_p, \tau)] = 0,$$

where the heat-transfer coefficient α is determined from the criterial equation [5-7] $Nu = A + BRe^m Pr^n$. For a spherical particle in a hot gas stream ($Pr \approx 0.7$) with $Re = 10\text{-}100$ we have $Nu = 2 + 0.16\ Re^{2/3}$ [5].

It was shown in [4] that the final form of the solution of Eq. (1) is largely determined by the numerical values of the Fo and Bi numbers which can be estimated after actual parameters of the process have been specified.

As an example we will examine the heating of a polyethylene particle with the following initial data (the parameters of the burner, of the jet, and the operating regimes were chosen according to [1-3] so as to be most typical): $L_{fli} = 0.2$ m; $v_p = 20$ m/sec; $d_p = 150$ μm; $T_m = 873$°K. Then we have from [6] that $\lambda_m = 6.52 \cdot 10^{-2}$ W/(m•°K); $\nu_m = 96.89 \cdot 10^{-6}$ m²/sec, and according to [8], $\lambda_m = 0.45$ W/(m•°K); $a_p = 1.1 \cdot 10^{-7}$ m²/sec.

With the adopted conditions we obtain $\tau_{fli} = 10^{-2}$ sec; $Fo_{fli} = 0.196$; $Re = 30.96$, and $Nu = 3.54$. Then the heat-transfer coefficient $\alpha = 1470.3$ W/(m²•°K), and the Biot test is $Bi = 0.245$.

According to [4], the solution of Eq. (1), on condition that Fo and Bi are small, can be represented as

$$\theta = \frac{T(r, \tau) - T_0}{T_m - T_0} \approx 1 - \frac{r_p \sin\left(\sqrt{3Bi}\,\frac{r}{r_p}\right)}{r\sqrt{3Bi}} \exp(-3BiFo), \tag{2}$$

hence we obtain for the temperature at the surface

$$\theta_{sur} = \frac{T(r_p, \tau) - T_0}{T_m - T_0} \approx 1 - \frac{\sin\sqrt{3Bi}}{\sqrt{3Bi}} \exp(-3BiFo) \tag{3}$$

and at the center of the particle

$$\theta_c = \frac{T(0, \tau) - T_0}{T_m - T_0} \approx 1 - \exp(-3BiFo). \tag{4}$$

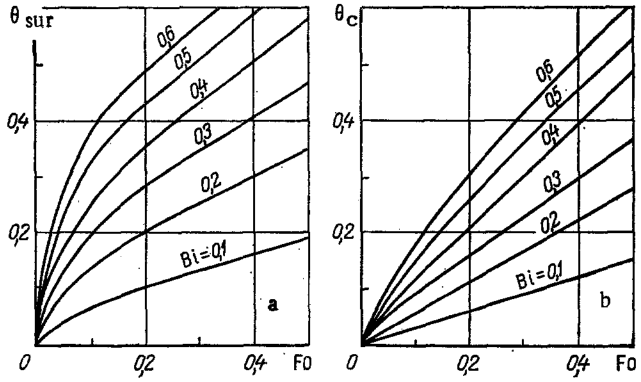

Fig. 2. Dependences $\theta_{sur} = f(Bi, Fo)$ (a) and $\theta_c = f(Bi, Fo)$ (b).

The Fo numbers corresponding to the onset of fusion of the particle ($Fo_{ons.fu}$) and to its complete fusion ($Fo_{c.fu}$) are described by the expressions

$$Fo_{c.fu} = \left| \ln \left[\frac{\sqrt{3Bi}}{\sin\sqrt{3Bi}} (1-\theta_{fu}) \right] \right| / (3Bi), \tag{5}$$

$$Fo_{ons.fu} = | \ln (1-\theta_{fu}) | / (3Bi). \tag{6}$$

The dependences $\theta_{sur} = f(Bi, Fo)$ and $\theta_c = f(Bi, Fo)$, obtained from expressions (3) and (4) (Fig. 2a, b), make it possible to carry out a preliminary analysis of the heating of a disperse polymer in gas-flame spraying and to choose the optimum parameters of the process. Expression (5) makes it possible to determine the time necessary for heating the particle surface to the onset of fusion, and expression (6) the time necessary for complete fusion of a particle with specified size r_p in the gas stream:

$$\tau_{c.fu} = \frac{2}{3} r_p^2 \frac{\lambda_p}{a_p \lambda_m} \frac{|\ln(1-\theta_{fu})|}{2+0{,}16\left(\frac{v_p d_p}{\nu_m}\right)^{2/3}}. \tag{7}$$

For the previously adopted conditions with $T_{fu} = 411°K$, $T_0 = 293°K$, i.e., $\theta_{fl} = 0.203$, we obtain $\tau_{c.fu} = 1.58 \cdot 10^{-2}$ sec, which is more than the adopted time of flight $\tau_{fli} = 10^{-2}$ sec. Thus, for gas-flame spraying the size of polyethylene particles that can be fused throughout has to be of the order of 100 μm.

In plasma spraying the radiant component q_r plays a considerable part in addition to the convective component q_c; for the solution of the problem of heating disperse material it is expedient to consider the differential equation of heat conduction in the form [4]

$$\frac{\partial T(r, \tau)}{\partial \tau} = a_p \left(\frac{\partial^2 T(r, \tau)}{\partial r^2} + \frac{2}{r} \frac{\partial T(r, \tau)}{\partial r} \right) \quad (\tau > 0;\ 0 < r < r_p) \tag{8}$$

with the following initial and boundary conditions:

$$T(r, 0) = T_0;\ T(0, \tau) \neq \infty;\ \frac{\partial T(0, \tau)}{\partial r} = 0;$$

$$-\frac{\partial T(r_p, \tau)}{\partial r} + \frac{q}{\lambda_p} = 0.$$

The flux density of the radiant energy q_r can be evaluated from the expression $q_r = Q_{absd}/NF_p$.

Since $F_p = 4\pi r_p^2$ and $N = \frac{3G_p \tau_{fli}}{4\pi r_p^3 \rho_p}$, and $\tau_{fli} = \frac{L_{fli}}{v_p}$ we have $q_r = Q_{absd} v_p / (F_{sp} G_p L_{fli})$.

The amount of absorbed radiant energy Q_{absd} is determined by the expression [6, 7]: $Q_{absd} = A_p Q_{sou}$, and in turn $Q_{sou} = c_0 \varepsilon_{rd} F_1 \overline{\varphi}_{1,2} \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_{sur}}{100}\right)^4 \right]$.

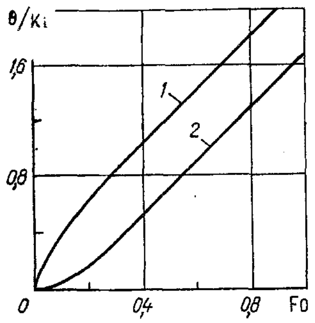

Fig. 3

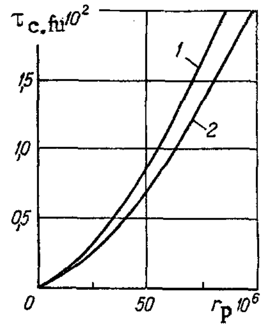

Fig. 4

Fig. 3. Dependences $\theta/\mathrm{Ki} = f(\mathrm{Fo})$ for the surface (1) and the center (2) of a spherical particle.

Fig. 4. Dependences $\tau_{c.fu} = f(r_p)$ in gas-flame (1) and plasma (2) spraying with disperse polyethylene. $\tau_{c.fu}$, sec; r_p, m.

The reduced degree of blackness of the system ε_{rd} for the given case [5, 7] is found from the expression

$$\varepsilon_{rd} = 1/\left(\frac{1}{\varepsilon_{sou}} + \frac{1}{\varepsilon_p} - 1\right),$$

but since for a polymer $\varepsilon_p \approx 0.15$–$0.2$ [9], and for monatomic and biatomic gases $\varepsilon_m = 1$ [7], we have $\varepsilon_{sou} \approx 1$ and $\varepsilon_{rd} \approx \varepsilon_p$.

Since for the conditions of plasma spraying $T_1 \gg T_{sur}$, and $\bar{\varphi}_{1,2} = \bar{\varphi}_{2,1}F_2/F_1$, we may write approximately: $Q_{sou} \approx c_0\varepsilon_p F_2\bar{\varphi}_{2,1}(T_1/100)^4$. Here $\bar{\varphi}_{2,1}$ is the exposure factor, $\bar{\varphi}_{2,1} = F_1/(\pi h^2)$.

The absorptivity of the flux is evaluated by the expression $A_p = 1 - \exp(-k_p F_{sp}\mu L_{fli})$ [7], where

$$k_p F_{sp} = \frac{0{,}42B}{\rho_p d_p}\sqrt{T_m};$$

B = 0.08–0.2 [7] is a coefficient depending on the type of particle. Then we have for q_r

$$q_r = c_0\varepsilon_p[1 - \exp(-k_p F_{sp}\mu L_{fli})]\frac{v_p F_2}{F_{sp} G_p L_{fli}}\left(\frac{T_1}{100}\right)^4\frac{F_1}{\pi h^2}.$$

Adopting $R_s/L = \beta$ (for typical cases of jet parameters $\beta = 0.24$–0.3 [2]) and $F_2 = \pi R_2^2 = \beta^2\pi h^2$, we may write the final result:

$$q_r = c_0\varepsilon_p\beta^2[1 - \exp(-k_p F_{sp}\mu L_{fli})]\frac{v_p F_1}{F_{sp} G_p L_{fli}}\left(\frac{T_1}{100}\right)^4. \tag{9}$$

According to [4], the solution of Eq. (8) with $\mathrm{Fo} < \mathrm{Fo}_1 \approx 0.5$ in generalized variables has the form

$$\theta = \mathrm{Ki}\frac{r_p}{r}\left[\exp\left(\mathrm{Fo} - \frac{r_p - r}{r}\right)\mathrm{erfc}\left(\frac{1 - \frac{r}{r_p}}{2\sqrt{\mathrm{Fo}}} - \sqrt{\mathrm{Fo}}\right) - \mathrm{erfc}\,\frac{1 - \frac{r}{r_p}}{2\sqrt{\mathrm{Fo}}}\right], \tag{10}$$

and hence for the center of the particle (r = 0) we obtain

$$\theta_c \approx 2\mathrm{Ki}\left\{[\exp(\mathrm{Fo} - 1)]\,\mathrm{erfc}\left(\frac{1}{2\sqrt{\mathrm{Fo}}} - \sqrt{\mathrm{Fo}}\right)\right\}. \tag{11}$$

Consequently, during the period of heating of the particle $\theta = f(\mathrm{Ki}, \mathrm{Fo})$. The nature of the change of the relative temperature of the surface and at the center of a spherical particle is shown in Fig. 3 [4]. If the obtained dependences are to be utilized in practice, it is indispensable to have data on the magnitude of the full heat flux q, i.e., q_c and q_r have to be determined.

The convective component q_c of the full heat flux q can be evaluated from the expression

$$q_c = \alpha (T_m - T_{sur}), \tag{12}$$

and q_r from expression (9).

As an example we will examine the heating of a polyethylene particle with the following data (the parameters of the plasma generator and the operating regimes were selected from the data of [1-3] as the most typical ones): $G_p = 1.5$ kg/h; $R_1 = 2 \cdot 10^{-3}$ m; $L_{fli} = 0.2$ m; $v_p = 80$ m/sec; $\beta = 0.25$; $T_1 = 20{,}000$°K; $d_p = 150$ μm; h = 0.05 m; $T_m = 1473$°K. Then we have from [6]: $\lambda_m = 9.15 \cdot 10^{-2}$ W/(m•°K); $a_m = 316.5 \cdot 10^{-6}$ m²/sec; $\nu_m = 233.7 \cdot 10^{-6}$ m²/sec, and from [8, 9]; $\lambda_p = 0.45$ W/(m•°K); $a_p = 1.1 \cdot 10^{-7}$ m²/sec; $\rho_p = 973$ kg/m³; $\varepsilon_p = 0.15$.

For the adopted conditions we obtain $\tau_{fli} = 2.5 \cdot 10^{-3}$ sec; $Fo_{fli} = 0.049$; Re = 53.70, and Nu = 4.22. The heat-transfer coefficient $\alpha = 2574.2$ W/(m²•°K) and the convective component of the heat flux (we assume that $T_{sur} = 411$°K) is $q_c = 2.73 \cdot 10^6$ W/m².

Since with the previously chosen conditions $k_p F_{sp} = 11$ m²/kg, $\mu = 0.0425$ kg/m³, $A_p = 0.089$, $F_{sp} = 41.4$ m²/kg, and $F_1 = 1.26 \cdot 10^{-5}$ m², the radiant component q_r of the full heat flux to the particle is equal to $q_r = 2.23 \cdot 10$ W/m², and $q = q_c = q_r = 4.96 \cdot 10^6$ W/m².

Then the Kirpichev test ($T_0 = 293$°K) Ki = 0.7, and we obtain from expressions (10) and (11) (see Fig. 3) $Fo_{fli} \approx 0.05$: for the surface of the particle θ/Ki = 0.26, and for its cen- 0.01, and consequently, $\theta_{sur} = 0.182$ and $\theta_c = 0.007$.

Finally we have $T_{sur} = 508$°K, and $T_c = 301$°K, i.e., with the given conditions of conducting the process, the polyethylene particles with the adopted sizes are not completely molten. The surface temperature of such a particle during its flight rises considerably above the melting point, approaching the temperature of ablation. With the adopted conditions of plasmotron operation only particles smaller than 50 μm will be completely molten.

The calculations show that in plasma spraying with polymer materials the radiant component of the heat flux plays quite a substantial part in the processes of heating disperse material, and this role is all the more important, the greater the dispersity of the material is. With decreasing r_p the absorption factor A_p increases, and consequently q_r increases, too. This reduces additionally the time necessary for complete melting of the particle.

The results of the calculation of gas-flame and plasma spraying with polymer material by the above-described methods are presented in Fig. 4 in the form of the depencences $\tau_{c.fu} = f(r_p)$ plotted according to the expressions (7) and (11). We see that with equal time of dwelling of the particle in the stream (equal τ_{fli}) the plasma process makes it possible to spray powders with substantially larger particles. Since the plasma process is characterized by the short dwelling of the particles in the stream (the speed in the flight of the particles is much higher, and the time of flight naturally shorter), particular attention should be given to the choice of the particle size of polymer material and to the uniform particle size distribution in accordance with the parameters of the plasma generator and the spraying conditions.

The relations obtained here make it possible to evaluate preliminarily the limit size of the particles that are fully molten in the gas-thermal processes, account being taken of the properties of the sprayed material as well as of the parameters of the stream and the operating regime of the sprayer.

NOTATION

L, distance between the nozzle edge of the aprayed surface; L_{fli}, path length of the polymer particle in the stream; F_1, F_2, F_s and R_1, R_2, R_s, sections and radii of the jet at the nozzle edge, in the zone of feeding of material, and on the protected surface, respectively; h, distance between the nozzle edge and the zone of feeding material; β, taper of the jet, $\beta = R_s/L$; q, q_r, and q_c, total heat flux density to the particle, its radiant and convective components, respectively; T_1, temperature of the source; T_m, temperature of the medium, T_0, initial temperature of the particle; τ_{fli}, time of flight of the particle; v_p, speed of the particle in the stream; G_p, mass flow rate of the polymer material; λ, thermal conductivity; a, thermal diffusivity; ν, kinematic viscosity; α, heat-transfer coefficient; ρ, density; Pr, Prandtl number, $Pr = \nu_m/a_m$; Ki, Kirpichev test, $Ki = q r_p [\lambda_p (T_m - T_0)]^{-1}$; Nu, Nusselt number, $Nu = \alpha d_p/\lambda_m$; Re, Reynolds number, $Re = v_p d_p/\nu_m$; Fo, Fourier number, $Fo = a_p \tau/r_p^2$; Bi, Biot number, $Bi = \alpha r_p/\lambda_p$; r_p, d_p, radius and diameter, respectively, of the particle; k_p, integral beam attenuation factor; F_{sp}, specific surface of disperse material, $F_{sp}=3/(r_p\rho_p)$; μ, mass concentration of particles in the stream, $\mu=G_p/(v_pF_2)$; c_0, coefficient of release of radiation by an absolute blackbody, c_0 = 5.67 W/(m²·°K⁴); N, number of particles in the stream; A_p, absorptivity of the disperse stream; $\varphi_{2,1}$, exposure factor, $\overline{\varphi_{2,1}}=F_1/(\pi h^2)$; Q, amount of thermal energy; ε, degree of blackness of the system; ε_{rd}, reduced degree of blackness of the system; θ, generalized temperature. Subscripts: m, gaseous medium; p, polymer; sur, particle surface; c, center of particle; fu, fusion; abl, ablation; sou, source; absn, absorption; fli, flight; ons.fu, onset of fusion; c.fu, complete fusion.

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PROPAGATION OF SOUND PERTURBATIONS IN HETEROGENEOUS GAS—LIQUID SYSTEMS

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UDC 532.59:534.22

It is shown that the spatial heterogeneity of the gas content and the disperson of sound in a bubble-containing medium may lead to deviation, focusing, and defocusing of sound beams.

Analysis of the processes that occur during the passage of pressure waves through a gas—liquid mixture having a bubble structure is required for solving problems of energetics and pipeline transportation. Wave propagation in gas—liquid media was investigated in [1, 2] in the approximation of plane one-dimensional motion. However, experimental data on gas—liquid flows in pipes suggest that the parameters of the mixture (for example, the spatial gas content [3, 4]) are not homogeneous over a cross section of the pipe. The present work is devoted to revealing the features of the propagation of the sound perturbations in heterogeneous gas—liquid media.

The equations of continuity and impulse for a single-velocity gas—liquid mixture are of the form

$$\frac{\partial\rho}{\partial t}+\operatorname{div}(\rho\mathbf{v})=0,\ \rho=\rho_1^0\alpha_1+\rho_2^0\alpha_2,\ \alpha_1+\alpha_2=1,$$
$$\rho\frac{\partial\mathbf{v}}{\partial t}+\rho(\mathbf{v}\nabla)\mathbf{v}=-\nabla p,\ p=\alpha_1p_1+\alpha_2p_2. \quad (1)$$

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